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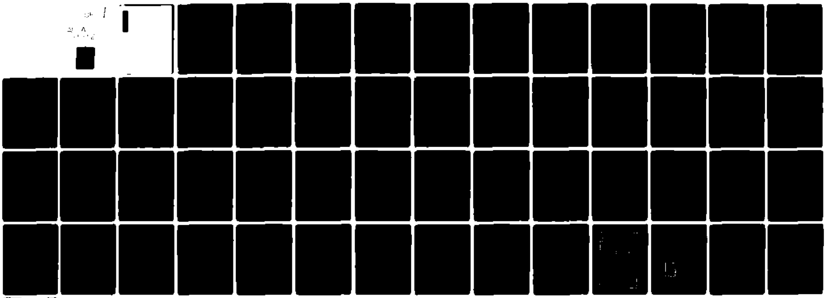

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A meeting was held March 11-15, 1980, to develop and refine the hierarchy of problems to be addressed by the high energy benthic boundary layer experiment. This document outlines revised program goals and the critical scientific tasks needed to attain those goals. Also included is an interim "state of the program" report and a critical review by the Advisory Committee.

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PROCEEDINGS OF THE KEYSTONE III CONFERENCE HELD AT THE KEYSTONE CENTER FOR CONTINUING EDUCATION MARCH 11-15, 1980.

-BY-

(10) CHARLES D. HOLLISTER, ARTHUR R. M. NOWELL AND J. DUNGAN SMITH

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TECHNICAL REPORT

Prepared for the Office of Naval Research under Contract (15) *N00014-79-C-0071; NR 083-004.*

APPROVED FOR DISTRIBUTION John A. Ewing

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Foreword

At the Third Annual Meeting of HEBBLE Principal Investigators, Program Managers and invited guests, it was generally concluded that the HEBBLE Project has successfully weathered the problems of childhood and is now a fully developed, multi-disciplinary, multi-institutional deep-ocean scientific effort. There are still some areas that need attention, but these may now be addressed within the framework of a coherent, directed experiment.

This may have been the last Keystone meeting as such; in retrospect I feel that the high mountain environment contributed to the success of these formative meetings. It is also my opinion that the more cantankerous the people and problematic the issues, the more important the "setting" factor becomes. The "Keystone Process" has worked successfully; contributing greatly, if not critically, to the overall goals of our Project.

The first meeting in 1978 represented the initial gathering of recognized experts from various oceanographic disciplines and provided an opportunity for direct interaction and verbalization of ideas; a process essential to the success of a large and complex program. The formal morning plenary sessions and evening group discussions, and the very informal afternoon sessions (which often took place on the chair lift or in the jacuzzi) were unanimously recognized as being both effective and uniquely productive. The scientific rationale and essential objectives outlined at that meeting have remained intact though subsequent restructuring of the program has occurred.

The second Keystone meeting was likewise an experiment in communication stretching across broad areas. It was specifically aimed at establishing communication ties between the oceanographic community and the space-age technological community represented by the Jet Propulsion Laboratory and NASA. After a number of false starts and nearly dead ends, the meeting concluded with a strong feeling that oceanography in general, and the HEBBLE Project in particular, would gain substantially by closer collaboration with state-of-the-art engineering, particularly with respect to in-situ data processing, communications and the design of remote, manipulative autonomous systems (e.g. the Central Lander and Seaflume). Again, the Keystone process was effective in obtaining consensus. The marriage of somewhat slapdash "take-it-to-sea" oceanographers with the penultimate, redundant capabilities of NASA required particular closeness, trust and a high degree of communication, all three of which were developed in this beautiful environment.

This third Keystone meeting of the HEBBLE participants, reported herein, was really the first substantive gathering of these parties into a single unified and dedicated effort; engineers, biologists, geologists and physicists all working together on an exciting and enjoyable project.

The "basic team" of HEBBLE is now pretty well defined: our PI's have stuck with the project through its first three tumultuous years. The group has by design been kept small, friendly and effective. This is not to say that it is a closed shop; in fact, those readers that see a natural interface between their research interests and an obvious need within the program are more than welcome to communicate with the Project Director or the appropriate PI directly. It would be particularly effective or useful if potential PI's pay close attention to the Advisory Committee Report contained herein, inasmuch as this report serves to outline research areas that need more attention.

HEBBLE is now in an action mode; the activities outlined in this document are the first solid steps toward our goal. Later reports will deal chiefly with actual data from the lab and field and will address the scientific implications of this information with respect to high energy processes on cohesive sea floor sediments. Our next HEBBLE Plenary Meeting will be in December, 1980, at the American Geophysical Union meeting in San Francisco, and there the first of these detailed reports resulting from our work, in the form of research papers, will be released.

At present, the HEBBLE project is supported almost entirely by the Office of Naval Research and to a lesser degree by NASA. It is also clear that this is a significant fraction of ONR's deep ocean support and therefore it is very appropriate for present or future PI's to continue considering other complementary sources of support for some of their research. Specifically, some of the larger scale scientific issues as outlined in this report may be more appropriate for National Science Foundation support. Also, engineering problems in the fields of power and data communication might well be done cooperatively with the Department of Energy's Subseabed Program, which is managed by Sandia Laboratories in Albuquerque.

Finally, there is a long-winded thanks contained within this preface to Robert Craig, President of Keystone Center, for helping the HEBBLE program attain air speed. I hope that the Keystone process will continue to serve other complex issues that require trust, consensus and balanced dialogue from people of widely divergent views; it has served HEBBLE well.

Charles D. Hollister

OUTLINE HIERARCHY OF HEBBLE I SCIENTIFIC PROGRAM

I. Site characterization
   A. Bed properties and geologic environment
   B. Gross flow properties and and Physical Oceanography

II. Establishment of parameters for integrated model
   A. High-frequency spectral characteristics of flow environment
   B. Parameters from field experiments
   C. Parameters from lab experiments
   D. Inner Layer suspended sediment behavior

III. Formulation of increasingly comprehensive BBL models
   A. Zero-order, unstratified
   B. Stratified, sediment entraining
   C. Time dependent
   D. Two-dimensional

IV. Field data gathering to test and refine models

V. Application of model and data to geologic and physical oceanographic processes

FIELD PROGRAM

I. April '80 - Site characterization
   A. Pogo camera: verify crag and tail region and distribution of larger scale periodic bedforms
   B. CM, BOM, SPM transmissometry, BASS: provide time series for calculation of exceedance statistics needed in design of conditional sampling program, engineering tests
   C. Hydrography: local time series
   D. Geological coring: texture, mineralogy, etc.
   E. Biological coring: functional grouping, pelletal characteristics, etc.

II. September '80 - Variability of hydrodynamic parameters of the bed
   A. Eight deployments of BASS in continuous sampling mode: establish variance of z_0, provide continuous wave-number spectral information
   B. First stereo pairs: variogram of surface microtopography
   C. SPM conditional mode sampling: test against April unconditional mode sampling
   D. Seaflume: U_{*cr} erosion (crude)
   E. CM, TRIFFID, BOM: time series, spatial coherence
   F. CTD: slope of isopycnals
   G. Pick up CM, BOM

III. August '81 - <u>Deep Tow detailed site survey</u>

IV. September '81 - <u>Pretest of model, especially averaging times</u>
   A. BASS in burst sampling mode: test stability of time-averaged means (with BASS)
   B. Seaflume: U_{*cr} erosion (rough)
   C. Navigated photos and cores (Deep Tow transponder network): as directed by April '80 and August '81 cruises
   D. Pick up CM, TRIFFID, BOM, transponders

V. Post - '81
   A. D-duct: U_{*cr} erosion (precise), U_{*cr} deposition, erosion rate
   B. Etc. (as necessary from pre-test results)

VI. '84 - Field test of Ekman layer-sediment transport models

LABORATORY PROGRAM

I. Objectives
   A. To determine effects of microtopography on z_0 and thereby to place realistic limits on roughness z_0
   B. To test sediment transport model for biologically altered, cohesive materials
   C. To obtain crude estimates of model parameter values for cohesive sediments from reconstituted field samples

II. Approaches
   A. Relate z_0 to topographic variogram
   B. Test for non-cohesive behavior
      1. Transport of non-cohesive particles (e.g. foram tests, sand) over clay bed
      2. Transport of fecal pellets over clay bed
   C. With and without shallow-water biological analogues
      1. Erosion rates
      2. Critical erosion and deposition velocities for varying textures and organisms
      3. Suspended sediment concentration profiles and settling velocities.

INTERIM REPORT OF THE HIGH ENERGY BENTHIC BOUNDARY LAYER EXPERIMENT

(The "Nowell Report")

The aim of the High Energy Benthic Boundary Layer Experiment (HEBBLE) is to increase dramatically our understanding of the flow dynamics and geological effects of strong flows in the deep-ocean benthic boundary layer.

Prologue

Until a few years ago, very little was known about interactions at the bottom boundary of the oceans. Geological and biological studies on the sea floor emphasized the description and cataloging of existing features and fauna. Relatively little thought was given to the processes which shape the sediment/water interface. Recent collection of sea floor photographs and sophisticated sonar data has sparked an interest among scientific and military communities in relating sediment movement and the formation of bedforms to the flow field of the boundary layer with which they interact. However, there are singularly few quantitative measurements on sediment movement to date.

To anyone inquiring about sediment movement associated with a given current, we can reply that there are only two or three sets of observations in which sediment movement was monitored at the same time that currents in the logarithmic layer were measured. If anyone asks whether the existence of certain bedforms (crag-and-tail, dunes, ripples, furrows, etc.) can be taken as a simple indicator of a certain current regime, we can only answer that intuition says yes, but we really have no theoretical or modeling basis for predicting the magnitude and duration of the current required to produce a given bedform in deep-sea, cohesive sediments.

Because we generally don't know whether the bedforms which now exist on the deep-sea floor formed in response to past or present conditions, we must undertake theoretical or modeling studies of certain kinds of sediment/bottom current interaction to guide our experimental design. Because our intuition and limited data suggest the need for longer than usual deployments of sensors on the sea floor and, conversely, our knowledge of boundary layer phenomena indicates the need for high-frequency sampling of short energetic "events", we must develop improved sensors and methods for conditional sampling of the environment, *in-situ* processing, and denser packing of the recorded data. While these theoretical, laboratory, and engineering studies are going on, we must consider the geographically limited state of our knowledge and continue exploratory studies of the distribution of high energy BBL areas. These exploratory studies will be combined with short deployments of presently available sensors that will feed back empirical results to modelers and theoreticians and help narrow the possibilities to be considered by engineers designing sensors, sampling plans and data recording systems.

Introduction

The entrainment of cohesive sediment, its transport as suspended load in the nepheloid layer and as bed load, and the generation of bedforms in marine muds are fundamental and unique problems. The geotechnical and sedimentological characteristics of the muds are modified directly by biological activities such as pelletization and tube building and indirectly through the addition of mucal polysaccharides. The physically-induced movement of such material results from fluid stresses operating on the boundary; the turbulent shear stresses in the flow are themselves influenced profoundly by the stratification of the boundary layer flow. The boundary stress, the entrainment of material, and the rate of sediment flux are the responses to forcing by an outer velocity field; the magnitude and variability of this outer velocity and its spatial extent both horizontally and vertically are as yet unknown.

The scientific goal of the HEBBLE program is to quantify the magnitude of deep ocean currents, their temporal and spatial variability, and to predict the response of the cohesive, biologically altered sediment to the imposed stresses. The transport of sediment as bedload, which results in dramatic bedforms, and the vertical flux and advection of suspended sediment, which give rise to high concentrations of material in the mixed layer, are the consequences of these imposed forces; the entrainment and transport of sediment will be examined, and dynamic influences of this moving sediment will be incorporated into a general predictive model of turbulent stratified Ekman layer transport over non-uniform topography.

The ultimate scientific goal is so ambitious, however, that a methodological hierarchy of problems has been developed, each stage of which represents an attempt to integrate state-of-the-art models of momentum transport and sediment transport with refined innovative instrumentation and careful, controlled laboratory experiments. The immediate goal, in the next four years, is to test a model of a stratified Ekman layer over small-scale cohesive bed roughness in the Western Atlantic. Such a goal requires that the near-boundary flow responsible for the shaping of the bed be measured precisely and that models of the boundary layer be developed to include the effect of stratification due to suspended sediment. Manipulative field experiments and laboratory studies to evaluate the influence of organism activity on sediment properties, including geotechnical parameters and the resultant effects on critical shear stress, must be carried out in order that the boundary layer model includes a realistic sediment transport model. Long-term experiments to measure the characteristics of the Ekman layer and short-term experiments to measure the flow in the logarithmic region must be carried out in order to measure the scales of variability of the stress, velocity, and sediment flux fields so that the time-dependent structure of the flow may be modeled. Subsequent experiments in regions

of larger scale bed forms, and experiments specifically designed to describe and model the advection of suspended sediment are vital subsequent steps in the HEBBLE program.

The long-term HEBBLE experiment will utilize an inverted recirculating flume to determine significant bottom properties and rate processes in-situ, and a Main Lander to conduct the central functions of the experiment. An important element in the design and fabrication processes for these instruments will be the involvement of JPL funded through the Technology Transfer Program of NASA. The technology, as well as a new approach to complex ocean problems, being transferred includes autonomous vehicle design and adaptive data acquisition from a variety of sensors.

There are at present two major themes in HEBBLE: (1) flow-boundary interaction which requires that the critical erosion velocities be measured and interpreted in terms of the significant geological and biological parameters, and that the momentum field in the boundary layer be known for input to a turbulent Ekman layer model; and (2) sediment flux studies which also require a precise model for the vertical flux of material.

Methodology

The precise goal of the HEBBLE program in the next four years is the implementation of a boundary layer and sediment transport model and its field verification to predict sediment transport in areas of strong bottom boundary layer flows in the deep ocean. Such a goal will thus allow us to describe the genesis of bedforms found in cohesive sediments and to estimate local sediment flux. To make progress towards this goal and in understanding the transport of sediment in the deep ocean, a series of experiments, coupled with laboratory modeling and extensive geological and biological taxonomic work, is proposed; such work will be carried out in concert with the modeling of the benthic boundary layer and its sediment transport.

We take as our central methodological tenet that progress in science is made only when a testable theory is examined unambiguously. This tenet rests on one axiom: the singular test of any theory is whether it provides acceptable answers to interesting questions about important problems.

There can be little debate that the deep ocean boundary layer presents many interesting questions; but are they important problems? Methodologically, important problems may be defined as shared empirical problems. The problem of the prediction of sediment transport in the deep ocean is shared by physical oceanographers concerned with ocean mixing and the diffusion of scalar quantities; by biologists who are attempting to model foraging strategies within soft-bottom benthic communities; by geomorphologists trying to describe the bedforms and

their mode of formation in the deep ocean; and by sedimentologists who wish to infer from bedforms in the stratigraphic record the direction and magnitude of the paleo-currents.

Most work on marine sediment transport in the past has been equivocal: observation and measurement have not usually been in strong accord with prediction. However, this disparity is often due either to the operation of intervening variables not explicitly included in the predictive model (non-uniformity in the momentum field; biological alteration of sediment characteristics; dynamical influences of suspended sediment not properly incorporated in a model; inadequate characterization of the hydrodynamic properties of the sediments) or to uncertainty in the accuracy of the data (averaging times too short being the most common problem).

Pragmatically, important problems may be defined by the criteria of the breadth of applicability of their results, their timeliness and their likelihood of solution. The breadth of applicability of results from HEBBLE has been addressed in great detail elsewhere (HEBBLE Report 1978, WHOI-78-48). Mining, drilling, and seabed disposal require accurate predictive models of sediment transport under a wide variety of imposed stresses. Deployment of structures on the seabed and the subseabed disposal of radioactive waste require knowledge of the integrity of the sediment and of the erosional and depositional character of the bed as well as the current strength and variability. The likelihood of a satisfactory solution depends upon a preliminary knowledge of the subject and the methodology adopted to arrive at a well-founded, testable hypothesis. The interdisciplinary structure of the HEBBLE program is a necessary prerequisite to the development of a suitable methodology. A precise goal is required for the next four years of the HEBBLE program so that simple models and controlled laboratory studies may be integrated successfully with the field research.

The timeliness of the HEBBLE program stems from two sources. The recent development of innovative instrumentation, such as the acoustic stress sensors and the acoustic and optical transducers for measuring suspended sediment concentration, and of data logging systems and microprocessor controls to permit long-duration adaptive sampling schemes, will allow the precise testing of state-of-the-art Ekman layer models. The HEBBLE project, moreover, will produce results that can be compared directly with the current NSF program CODE (Coastal Ocean Dynamics Experiment) working in shallow coastal regions. That study is measuring Ekman layer characteristics and examining the spatial variability in boundary stress. HEBBLE will complement such studies by working in a simple region away from high-frequency wave influences but in areas of cohesive bed material.

Other in-situ deep-ocean experiments are being undertaken at present (ISHTE: In Situ Heat Transfer Experiment, Sandia Lab Report 2219), though only in low energy environments. HEBBLE is the only experimental program with significant boundary layer, biologic and sediment transport components.

The lack of knowledge on the temporal variability of currents sufficient to entrain material from the bed in the deep ocean means that HEBBLE has need for a structured program that will evaluate both the critical stress required to move such marine muds and the frequency of currents of that magnitude. Hence, HEBBLE will produce an expository model using developed Ekman layer models rather than developing a definitive predictive numerical scheme.

The immediate goal of HEBBLE is the development of a model and its field verification to predict sediment transport in areas of strong bottom boundary layer flows in the deep ocean. The inputs will be the sediment characteristics, both biological and physical, the flow field and the boundary topography. The initial site will have small-scale distributed roughness so that simple one-dimensional models may be rigorously tested. Subsequent experiments in regions of periodic bedforms such as furrows and mud waves will be investigated once the first-order problem concerning sediment entrainment and the scales of variability of the shear stress in the turbulent boundary layer has been adequately modeled. The important but complex problems associated with the advection of material in the nepheloid layer will be addressed successfully only when simple local models of sufficient accuracy have been verified.

The shared nature of the problem offers some unique opportunities. Geotechnical measurements, long presented as an appendix to work on cohesive sediments, can be integrated with the biological research on mucal polysaccharide concentrations. Textural measures routinely obtained by geologists may be examined in the light of biological studies of particle selection by deposit feeders and fecal pelletization. In-situ manipulative experiments on the rate of biological reworking using an inverted flume will provide significant input, not only to biological foraging models but also to stratigraphic models of abyssal regions. Such conjoint studies form the basis for the HEBBLE project.

An important characteristic of the HEBBLE program will be the sharing of data among the Principal Investigators. While certain sensors have been selected, some because of their ability to provide unique data and others because of their proven records, this will not lead to territoriality with respect to the data. It is necessary that the expertise of experienced field scientists be integrated with the modeling capabilities and instrumentation competence of other P.I.'s.

Any proposal for scientific research and equipment development that falls within the HEBBLE purview will, moreover, be evaluated by two criteria: the significance of each particular program within its field, and its priority as a contribution to the overall HEBBLE goals.

Program Plan

The HEBBLE program consists of four major categories: (1) site characterization; (2) Ekman layer modeling and sediment transport modeling; (3) short- and long-term boundary layer experiments; and (4) controlled laboratory studies.

(1) Site selection and characteristics

A region on the Scotian Rise has been chosen for more detailed site selection studies. The criteria for the selection are well developed and numerous visual evidence (photographs) of currently active bed modification, simple crag-and-tail roughness that is uniform over a large area, and profiles of suspended sediment concentration which show values measured in thousands of micrograms per liter, all of which are strongly indicative of active erosion. Subsequent experiments in topographically more complex areas are envisaged. Initial measurements of the near-bed velocity and hydrography and qualitative estimates of suspended sediment load are being carried out currently (1979-80; Wimbush, Biscaye, Gardner, Zaneveld, Weatherly).

Site surveying using Deep Tow is vital not only to describe the large-scale bed topography and classify the bedforms, but also (in combination) to provide precise spectra of the bed roughness. As the profile of Reynolds stress is to be measured within two meters of the boundary, the upstream topography with scales on the order of 1 cm must be measured for an upstream distance of approximately half a kilometer. This will be achieved photographically (using either ANGUS or Deep Tow depending on state-of-the-art and final location of the site) just prior to the main lander deployment. Deep Tow (Spiess, Lonsdale), using high resolution bathymetric profiling, 120 KHz side-scan sonar and 4-6 KHz sub-bottom profiling, will provide the large-scale mapping and remote sensing of geological structure and variability. Such information is necessary to determine sites for preliminary biological and geotechnical sampling. A sequence of candidate sites in regions of increasing topographic complexity will then be selected.

An array of current meters is being deployed this year to give more information on the location of the core of the western boundary flow and the magnitude of its lateral movement. This preliminary work must be extended over the next three years to map more accurately the coherent length scales in the bottom mixed layer region. Temperature and possibly conductivity sensors must be provided with each current meter

so that a clearer picture of the water mass variability is obtained. At least seven moorings, following Wimbush's proposal, must be maintained over this three-year period. Such results are important not only to HEBBLE but to the broader interests in the near-bed deep-ocean dynamics studies. (North East Atlantic Dynamics Study is maintaining seven moorings over the next two years.) The lack of long-term moorings with near-bed current meters on the Scotian Rise in water depths greater than 3500 m is a serious omission to any study of the larger-scale dynamics of deep-ocean circulation. A much broader physical oceanographic program can be easily envisaged: the present program will provide the minimal level of information necessary for HEBBLE.

Arrays of current meters (Wimbush, Weatherly), thermistors (Irish, Weatherly), and transmissometers (Zaneveld) must be deployed prior to the Deep Tow study so that bedform and gross boundary flow characteristics can be integrated early on in the study. A set of transponders (Lonsdale) will be deployed so that box cores and gravity cores (Jumars, Yingst, Aller, Silva) may be located precisely within the Deep Tow site. Biological sampling (Jumars, Thistle, Yingst) will be carried out for a) taxonomic purposes including, insofar as possible, the resolution of functional groups of organisms and (b) for variance estimates of faunal abundances as a precursor to manipulative experiments. This work will also describe local bed roughness (Hollister, Tucholke) and integrate with the geological measurements on particle size, texture and variability and with the geotechnical measurements on vane shear strength and water content (Silva). The box cores will also be used to determine mixing rates using radionuclide methods (Biscaye, Gardner).

Initial determination of critical erosion stress is to be attempted using Southard's flow-through seaflume with correlative vane shear and water content measurements made on gravity cores taken during deployment. In order to obtain measurements of critical erosion and deposition stress as well as the essential <u>rates</u> of erosion and deposition requires a recirculating bottom flume, the Sea Duct, to be designed at JPL and WHOI. Sensors to be mounted on the duct will include: a laser-Doppler velocimeter for measuring profiles of the Reynolds stress, velocity and suspended sediment concentration; a miniature shear vane and a camera. The flume will be designed to return with some of the bed from both inside and outside the housing so that biological and standard geotechnical and geological sampling may be carried out.

To set the near-bed measurements in the correct fluid mechanical context, measurements of the flow at many scales in the whole Ekman layer must be carried out. The physical oceanographic component of HEBBLE is at present a service yielding information only sufficient to model the Ekman layer (Weatherly, Wimbush). Preliminary measurements to

determine cross-current and down-current coherence in the Western Boundary Under Current are being carried out to allow some generalization of the results from HEBBLE (Hogg). But such questions concerning the deep circulation in the Western Atlantic are not being addressed at present. Part of the long-term goal of HEBBLE is to predict the rate of movement of the bedforms found in the deep ocean, and thus it is important that large-scale surveys of the flow and of the hydrography be caried out. Questions concerning the origin of the water, its variability, and the presence of, for example, mesoscale eddies close to the boundary should also be addressed. These questions, however, are seen at present as being of secondary importance; until sensible interpretation and prediction of the critical entrainment stress and the scale and variability of the Ekman layer are modeled adequately and fully documented, such results on larger-scale variability cannot be adequately related to the boundary layer structure or to the bedforms observed.

Much currency has been given to ideas of intermittency in geophysical boundary layers, and the notion of coherent eddies in turbulent boundary layers has gained many advocates. Coherent structures within the mixed layer (at scales very much larger than the mixed layer thickness) have been documented by Armi from current meter records placed above the logarithmic layer (lowest record 15 m from bed). Coherence of events at scales of boundary layer thickness and greater will be examined as part of HEBBLE utilizing standard time series techniques to investigate correlations of velocity, temperature, and light transmission between the out-stations (see Section 3). Intermittency (bursts and sweeps) as discussed by many laboratory fluid mechanists will need first to be investigated in rough wall sediment-transporting flows before the scaling arguments can be transferred to the high energy benthic boundary layer. Such work is proposed in Section 4. If the scaling is applicable then the period between bursts T ($\simeq 5D/U_\infty$ with $U_\infty \simeq 40$ cm s^{-1} and D = 30 m) is approximately five minutes: well within the resolution of the acoustic stress sensors. However, until boundary layer models include intermittency, bursting and coherency, it is inappropriate to focus our experimental program on such chimerical properties of the flow. The success of time-averaged second-order closure models (Section 2) in many different flow environments suggests that their use and validation is the most expeditious route to follow.

The site characterization is itself of profound scientific importance; the temporal and spatial variability of the Western Boundary Under Current, its interaction with meso-scale eddies, and the variation in height of the mixed layer are all unknown. Detailed biological studies, geotechnical measurements and critical erosion measurements would, of themselves, be important contributions; moreover, their incorporation into an Ekman layer model with a realistic sediment transport component would constitute a unique and potentially very

significant contribution to our understanding of deep-ocean boundary layer processes.

(2) Boundary layer modeling

The modeling of the benthic boundary layer will provide a rigorous framework for the collection and interpretation of data on the velocity and stress fields in the near-bed region in the presence of possible stratification due to suspended sediment and temperature. It also forms the basis for generalization to greater modeling efforts using more than one-dimensional boundary layer models to describe the effects of advection over non-uniform topography. From recent studies, it appears that major erosional events, characterized by very high suspended sediment concentrations, affect the structure of the benthic boundary layer. To model such events which have time scales of order of a day, baroclinic effects must be included in the model as well as local stress-velocity field relations. A time-dependent model including stratification has already been developed (Weatherly) and will form the basis for the sampling design in the vertical array and the integration of the field measurements.

An important contribution to the modeling effort will be the inclusion of a sediment transport model, which will be developed as part of the laboratory studies on entrainment and transport of cohesive, biologically-altered muds (Nowell, Jumars). The results of the laboratory experiments will also be integrated with the inverted flume deployments at the HEBBLE site.

(3) Short- and long-term experiments

Short-term (three day) experiments will be carried out with the goals of measuring the velocity (Weatherly, Wimbush), stress fields (Williams), suspended sediment concentrations in the lowest two meters (Zaneveld) and of monitoring bed movement photographically (Hollister). These experiments will act to establish the lower boundary conditions for the Ekman layer model and will also provide information on the sampling rates, averaging times, and stability of estimates of computed parameters such as sediment flux. Careful consideration will be given to the assumption of stationarity of the parent process during these short-term deployments. Some limited work on the higher-frequency turbulent motions will also be carried out to insure that the stress co-spectra and energy spectra in the deep ocean are measured adequately by the acoustic stress sensors.

Flow measurements in the lowest two meters are being carried out currently (1979, 1980) using acoustic stress sensors (Williams) and hot-wire anemometers (Gust). Such work must provide averaged kinetic energy and stress measurements and the wave number distribution of these quantitites. Continuous recording of the acoustic stress results will

allow spectra to be computed for periods of over one hour so that sensible averaging criteria may be determined. The hot-wires must be placed at the same height as the acoustic stress sensors and the resultant spectral densities overlapped to obtain extensive wavenumber coverage. Overlapping the spectra and co-spectra for the hot-wires and the acoustic stress sensors will allow evaluation of the effect of spatial averaging and the frequency response of the Benthic Acoustic Stress Sensors (BASS); such a program may then remove the necessity for making high-frequency turbulence measurements in any of the longer-term deployments.

These initial short-term deployments will act as field tests for all the sensors, most notably BASS, ABSS (Acoustic Backscatter Sensor for Suspended sediment--Orr) and the transmissometers (Zaneveld). As all these instruments are relatively new, considerable effort will be made to calibrate them. Their sensitivity to variation not only in velocity but also in angle of attack will be established in laboratory tests and in large-scale boundary layer flows with well-documented characteristics prior to their deployment as part of the short- and long-term HEBBLE experiments. Calibration tests of BASS were successfully carried out in April 1980 in a large uniform flow canal (Williams, Nowell). Calibration tests of the transmissometers are scheduled for 1980 (Zaneveld, Biscaye).

The goal of the short-term (three-day) experiments is to provide information on the near-bed variability of flow parameters and suspended sediment concentration over periods when the motion is the result not only of a simple boundary layer shear flow, but also when internal waves and inertial wave effects are present. It is these latter effects that cannot be well simulated in laboratory flows. As the boundary layer may also be stratified, it is important that detailed measurements be obtained not only of the velocity and stress fields but also of the temperature structure (Irish) and suspended sediment concentrations (Zaneveld, Orr, Gardner, Biscaye) in order to evaluate the possibility of non-linear interaction of the time-dependent stratification with the slowly varying western boundary layer flow.

A series of three-day experiments will indicate suitable sampling rate, averaging time, and (possibly) stability of estimates of observed quantities which will be vital to early testing of the near-bed predictions of the second-order closure model. Some of these experiments must be carried out immediately so that the information can be used to design the sampling scheme for the long-term experiment; others must be carried out after detailed mapping of the topography by Deep Tow and local photo mapping (Hollister) upstream of the sensor arrays. In this manner the variability in the boundary stress profiles and the suspended sediment concentration profiles may be interpreted unambiguously. To aid in the examination of the short-term experiment results, simple eddy viscosity models incorporating stratification corrections and time dependence will provide a useful diagnostic tool

and valuable comparison with the Weatherly-Martin model. Considerable work on such models has already been carried out as part of the Shelf Sediment Dynamics Program and by the time the short-term experiments in HEBBLE have been carried out such models will be available at the University of Washington.

In shallow-water coastal regions, the time scale of erosive events is known to be controlled by the large cyclonic storm stresses (duration of two to three days). In the deep ocean very little quantitative information is available, and before questions of large-scale spatial variability in regions of bedforms can be addressed, the significant time scales of erosive events must be documented. Preliminary studies using Triffid (Wimbush) and the Bottom Ocean Monitor (Biscaye, Gardner) will be valuable in the next eighteen months. A sequential horizontal suspended particulate matter sampler (triggered by the OSU transmissometer to change the sample container) would provide some useful calibration information for the transmissometer and also allow us to examine some of the particles that are moving as suspended load. However, to develop a definitive measurement capacity which will interface usefully with the Ekman layer model, a long-term deployment of a major instrument complex is required. A main lander and four outstations are the minimum requirements for this experiment.

The long-term experiment will study in detail the fluid mechanics of the benthic boundary layer and associated sediment transport. The objective is to obtain a relatively long time series of turbulent stress, velocity, and suspended sediment concentration profiles in the near-bed region, and equally long time series on mean flow characteristics in the outer region of the benthic boundary layer. The experiment will have a main lander utilizing recently developed instruments, including omni-directional flow-measuring capabilities using three sets of acoustic stress sensors (Williams), three sets of acoustic particle concentration sensors (Orr) and a holographic particle velocimeter (Carder) to examine particle settling velocities in-situ. A vertical array of ten current meters with thermistors, ten conductivity sensors and ten transmissometers will be moored beside the main lander to provide a unique data set on the Ekman layer profile. Estimates of boundary stress from the BASS system, the near-bed velocity profiles in the logarithmic region and integration of the velocity profile in the outer Ekman layer will all be compared with the second-order closure and eddy viscosity model. Stratification corrections must be included in such models, for the preliminary measurements that have been carried out indicate that the boundary layer at any site in the Western Boundary Under Current may well be stratified by suspended material; hence it is vital that ABSS be included in the experiment. Sampling rates for ABSS should be determined from three-day experiments but should not exceed the sampling rate of BASS. Considerations of power requirements and data storage will determine the optimal sampling scheme, in concert with the preliminary measurements from the short-term experiments.

The movement of material along the bed, the modification of any local bedforms and the flux of sediment in the water column are key parameters in the short- and long-term deployments. While acoustic and light transmission measures will yield results on the suspended material, photographic studies utilizing a 35-mm stereo-pair camera (Hollister, Tucholke) will provide vital information on local bedform change, local relief, and even surficial biological activity. Some redundancy is desirable in this measurement, especially given the mechanical vagaries of cameras. A 16-mm camera system (Wimbush) would provide adequate backup. A narrow-angle camera (Biscaye, Gardner) will be considered for its potential to show individual particle motion. It is suggested that the oblique angle camera can be deferred until subsequent experiments when light transmission characteristics are known to be more favorable to side-angle photography. A pop-up camera (Biscaye) for initial site check will be required on the main lander. Other available camera systems (Wimbush, Biscaye, Hollister) might be deployed at the outstations so that more extensive information on bedload movement over the duration of the experiment is obtained.

The present study will attempt to measure with great accuracy the one-dimensional profile of velocity stress and stratification in the boundary layer over a long time period. This will be done in a region where the flow is likely to be dominated by very low-frequency unsteadiness and where the boundary layer structure may be strongly controlled by the transport of suspended sediment. While the results from the main lander and vertical array will be used to test a simple one-dimensional model, four outstations separated from the main lander by several kilometers will be instrumented with current meters, thermistors and transmissometers to provide concurrent information so that spatial coherence in the outer Ekman layer over the time scales of large-scale events may be examined. Such information is important in that it may provide initial estimates of spatial variability; in subsequent studies over topographically non-uniform areas, local effects (on the scale of the separation of the bed waves) may be more sensibly interpreted. Initial estimates of the scales of motion may facilitate the development of two- and three-dimensional models.

Knowledge of the hydrography of the free stream region above the benthic boundary layer is essential to the modelling efforts. We know from previous studies of the atmospheric and oceanic boundary layer that both the vertical and horizontal density gradients of the geostrophic interior have "zero-order" effects in determining the boundary layer structure. The fixed-level temperature and conductivity sensors are intended primarily to give detailed density data in the boundary layer with limited data above in the free stream region. Thus it will be critical that these fixed-level data be supplemented by data obtained in CTD casts (Zaneveld, Weatherly), particularly in the free stream region. It is important to extend the CTD cast well into the boundary layer to provide calibration data for the fixed-level temperature and

conductivity sensors (to make corrections for drift and offset), as well as to assure that the boundary layer is sampled suitably in the vertical dimension. Cross-stream transects and profiling next to fixed-level arrays are to be integral parts of HEBBLE cruises.

(4) Laboratory experiments

To integrate the inverted flume results and those from the short- and long-term experiments on sediment entrainment, a series of laboratory experiments is proposed. These measurements would focus on the criteria of sediment entrainment of cohesive material with and without organisms present (Jumars, Nowell, Collins).

Field sampling of biological community structure (Yingst, Thistle, Jumars), geotechnical (Silva) and sedimentological (Tucholke) properties will allow a series of laboratory experiments on sediment entrainment of biogenically-altered fine muds to be carried out. This work will evaluate the importance of biogenic roughness and biological alteration of sediments on the entrainment of cohesive material and hence will aim to integrate the geotechnical measurements made at the site. Simulations of cohesive sediment using modeling clay to achieve comparable shear strength characteristics have already proved useful in the ISHTE study and will be used as part of HEBBLE in flume studies to relate the critical stress measurements to shear vane results (Collins, Nowell). Marine muds, both abiotic and with macrofauna, will then be studied in a recirculating seawater flume using a laser-Doppler velocimeter so that precise stress, velocity, and suspended sediment concentraton profiles can be obtained in the presence of abundant mucal polysaccharides. This work, coupled with the inverted flume deployments, will provide the vital information on sediment entrainment for input to the second-order closure model utilized by Weatherly and Martin. Only in the laboratory can extraneous variables be controlled adequately for model development.

HEBBLE 1980 and Ancillary Plans

The instrument deployments in summer 1979 and 1980 will provide much-needed information on the stability of estimates of stress, velocity, and sediment flux. It is vital that wavenumber information on these quantities be available, as this will provide the greatest information on suitable averaging times. Some conditional sampling must be carried out subsequently to insure that conditionally-sampled data from the main lander experiment and short-term experiments can be used to validly describe the nature of the parent population from which they

are to be drawn. As mentioned earlier, metal-clad wires will be used in these 1979-80 deployments to extend the frequency range of BASS. If the spectra and co-spectra can be made to overlap (and they must, if either set of results is to be believable) then the monotonic declining spectral shape at high wavenumber can be evaluated and used to correct the stress estimates made by BASS. If, as expected, the spectra exhibit a strongly declining slope beyond that frequency measured by BASS, little further work on turbulence in the short- and long-term experiments is required. Metal-clad wires are sufficiently small that it might be useful to have four in the region below 25 cm (the lowest height of the acoustic stress sensor) in order that measurements of the mean velocity field could be made close to the boundary. However, the problem of keeping one sensor balanced has proved sufficiently daunting in most ocean microstructure studies (see Grant et al., 1962, J. Fluid Mechanics; Nasmyth-Oceanic Turbulence), and a serious alternative would be a laser-Doppler velocimeter that could range over the lowest 25 cm of the flow. The development of such a sensor would be of inestimatable value in ocean micro-structure work in general, and would have immediate and impressive value as part of the short-term experiments as a means of accurately measuring the mean velocity and hence providing a better estimate of the bed stress. It will be vital as a means of measuring the velocity field in the inverted flume to be deployed at many sites within the HEBBLE region.

Calibration of BASS will be carried out in April 1980 in a large-scale boundary layer flow. This test will provide information on the stress measuring capability of BASS in a well-documented, simple environment; it will also give some insight into the stability of estimates of stress and velocity in a steady boundary layer which will be useful to compare with the results in the more variable Western Boundary Under Current. Such calibrations are an important precursor to the main HEBBLE experiment and similar calibrations in laboratory flows will be carried out on the OSU transmissometers (Zaneveld) and its outputs in comparison with the LDGO nephelometer (Biscaye, Gardner). The response of the transmissometer to variations in angle of attack will also be evaluated. While the HEBBLE environment prohibits the use of most sediment traps because of the very high shear, the development of a horizontal flux sampler would be most useful. If subsequent HEBBLE experiments are to correctly address problems focused in the nepheloid layer, new instruments capable of resolving the spatial variability in horizontal particulate flux will be needed. Some effort (Biscaye, Gardner) will be directed towards this goal in the coming year. Calibration and response characteristics of ABSS must be well in hand by the end of 1980 in order that the system be available for the short-term experiments in 1981-82. These three groups of sensors (BASS, the transmissometers and ABSS) are seen as vital to the measurement program, providing essential basic information for the boundary layer models.

The biological program prior to the main lander deployment requires a pretest to obtain various estimates on the abundance of macrofauna, meiofauna, and microflora. Such information will then provide the necessary number of box cores to quantify the spatial patterns of functional groups, the biogenic microtopography, mucus concentartion and the biologcally-influenced geotechnical properties at the HEBBLE site. This work will then allow a series of relevant laboratory studies to be performed on the effects of burrowing, pelletization, and tube building on the sediment structure using organisms from similar functional groups but from shallow water. Integration of the geotechnical and biological results will follow; such information will be very germane to studies concerning the use of the inverted flume. If the flume is suitably instrumented so that Reynolds stress, particle concentration, bed stratigraphy and topography are measured, the critical shear stress results will be readily interpretable in terms of the laboratory results. Values for such parameters are a necessary input to the second-order boundary layer model and are essential also to the interpretation of the stratigraphic record. The interdisciplinary nature of marine sediment transport requires this degree of integration.

A series of laboratory experiments with analagous shallow-water organisms to examine the effects of biological activity on particle motion is required. While work on noncohesive sediments is already underway to give first-order estimates of the mechanisms of flow and organism and sediment interaction, an extensive laboratory program is required to allow prediction of significant biological effects on sediment transport at the HEBBLE site. As considerable quantities of material at the HEBBLE site move as suspended load, a suite of experiments to model the nature of entrainment and deposition in biologically altered cohesive sediments is required. It is anticipated that the race track flume to be built under SSDP at Friday Harbor can be used for this study. Such a facility is necessary if most of the material moves as suspended load, for putting the suspended sediment through a pump will alter or destroy the clay flocs, and hence influence the entrainment characteristics. A laboratory laser-Doppler system capable of both resolving the scales of motion and the large intermittent fluctuations in bed stress that might be anticipated and of accurately measuring in the presence of abundant mucus will be utilized for this study. Such results, when integrated with the inverted flume work, will form the basis for the development and testing of an adequate sediment transport model for cohesive marine clays.

Conclusion

HEBBLE is unique at two levels of scientific inquiry. At the level of exploratory science, it will provide information on the variability of currents in the deep-ocean boundary layer; few measurements within one meter of the boundary exist at present. It will yield primary data on biological community structure, geotechnical properties and the

concentration of suspended material in the bottom mixed layer over a long time period. However, at the level of predictive science, the development of a viable sediment transport model for marine muds while explicitly incorporating biological effects is of great significance. The utilization of such a model as part of a second-order closure scheme to describe the Ekman layer would be a major advance in marine boundary layer studies.

The interplay of theory, field observation, manipulative experiments and laboratory studies is required if the complex problem of marine sediment transport is to be addressed properly. The direct topographic effects and subtle influences due to mucus production of organisms will be evaluated so that sensible models of sediment transport can be incorporated into the closure model that is the starting point of the HEBBLE study. The HEBBLE experiment will utilize a topographically simple site initially so that the major problems of critical erosion velocity and the temporal variability and structure of the bottom boundary layer may be studied adequately.

SUMMARY OUTLINE OF CRITICAL SCIENTIFIC TASKS NEEDED TO REACH HEBBLE GOALS

(a distillation of Keystone III notes)

I. Inner Layer (less than 10m vertical, 1000 m horizontal)
  1. Bed Response to Stress
    a. Geology: Microtopography, texture, particle alignment, clay mineralogy, fine scale (cm) stratigraphy
    b. Geochemistry: Radionuclide mixing, rates of sediment accummulation, Eh, pH, organic carbon and nitrogen, radon for diffusion rates, cation exchange capacity
    c. Biology: Biogenous microtopography, pelletal characteristics, organism abundance, mucus/polysaccharide concentration, horizontal and vertical biogenous structure, laboratory determinations of how production and breakdown rates of fecal structures and physical disturbance affect critical erosion stress.
    d. Soil mechanics: Vane shear strength profiles on cores and in-situ, cylindrical penetrometer for shear strength, water content, porosity, bulk density, triaxial compression and consolidation characteristics, microstructure with SEM.

  2. Fluid Dynamic Parameterization
    a. Region: From bed through constant stress or log layer
    b. Goal: Parameterize flow to allow extrapolation of skin friction and thus critical shear stress
    c. Approach: Use simple, tested models, compare model prediction to measurements, expand and refine measurements and models.
    d. Zero-order model: "A constant stress or log layer exists and extends to the bed", assume uniform flow over smooth bed.
    e. Experimental plan: 1980 and '81 cruises will test this model by using independant instruments on same frame (BASS, crossed hot wires)
    f. First-order model: Add effects of suspended sediment as a stratification term, needs mass-concentration weighted settling velocity
    g. Future-order model: Add non-uniform bed structure and non-uniform flow

  3. Near-Bed Fluxes of SPM
    a. Space scales: Horizontal scales of erosion may vary from centimeters to kilometers (benthic storms); depositional scales range from patchy between rough bed features (crag and tail) to continuous over smooth beds.

b. Parameterization of an Event: The objective is to determine whether a sediment transport "event" is of local or distant origin, sharpness of onset and disappearance of SPM may be a function of relative horizontal transport distance; distant event may have lost larger particles thus there is a need to know size distribution and composition for crude horizontal scale estimation.

c. Time scales: Need to differentiate time scales of sampling vs. scales of events. Bursting phenomena is probably in minutes scale, storms may be days scales for duration and months scales for intervals.

d. Methods of measurement: Sampling frequency of 5-10 minutes for SPM concentration, can be done with transmissometers and nephelometer. Optical measurements are of order 20 times/sec. Below 3 m.a.b. bottom moorings (BOM, BASS, ABSS, Chandelier etc.) can be used to 10's of cms above bottom. Concentration-weighted settling velocities of particles will have to be determined (holographic, transmission, settling tube techniques) and near-bed gradients of SPM will require a stack of miniaturized transmission or scattering devices in the lowest 25 cm.

II. Benthic Boundary Layer (less than 100 m vert., 10 kms horiz.)

1. Model Development, Verification and Refinement

a. One dimensional model: Steady state, neutrally stratified, turbulent Ekman layer model has been verified in Florida Straits but region is not one-dimensional. This model should be tested in HEBBLE area with current profiles during time of low SPM concentration. One-dimensional profiling to within 3 m.a.b. with CTD, nephelometer, C-meter and water samples should be obtained concurrently with bottom-moored event-triggered experiment. Vertical gradient of SPM is needed to determine effects of stratification - particularly within 10 cm of the bed. Critical shear stress needed for erosion should be determined on reconstituted cohesive mud in laboratory flume and in-situ with SEAFLUME; the settling rate weighted by SPM concentrations is needed for various modeling efforts (Weatherly).

b. Two-dimensional model: Buoyant Ekman layer or Ekman pump on sloping bottom model; horizontal density (S, T, SPM) gradients are needed. Need "steady" flow of some weeks in control area "boxed" with outstations.

2. Flux and Dynamics of SPM

a. Scales of interest: Within the BBL, SPM should be studied at approximately km's horizontal and 100's of meters vertical dimensions; temporally this corresponds to

2000-20,000 seconds and 10-2000 seconds respectively, assuming horizontal velocities of the order 5 to 500 cm/sec.

b. Processes: The prediction of the progression of erosion events and SPM downstream and vertically requires knowledge of turbulence, mixing rates, settling velocity distribution and SPM concentration. Rates of accumulation/erosion over experiment duration requires an input-output box model approach; the longer time frame will require high quality coring with detailed examination of micro-stratigraphy.

3. Vertical and Horizontal Coherence of SPM, Flow and their Interaction -- "Events and How to Describe Them"

a. Event size: Results of recent cruises suggest that high energy events of 2-4 days duration occur with intervals of 2-3 weeks (or longer?); a sampling interval of 5-10 minutes for SPM is considered sufficient.

b. Some sampling considerations: The need for synoptic vertical profiles of SPM, S, T, etc. during an "event" may require, later in the program, a DEW line of "cheap" sensors connected to a shore facility responsible for ship (CTD) dispatch. Coherence between current meter records will be important input to the final distribution of horizontal spacing of sensors. Bottom current meters (with temp.) should be as close as possible to the sea floor and should be spaced logarithmically upwards. ABSS should endeavor to "see" the top of the mixed layer if defined by a sediment cap. Sediment traps produce an integrated picture of sediment transport sufficient for very large scale modeling but uninterpretable at the BBL scale of HEBBLE I. An important requirement is to determine whether changes in signal strength, at a point, are due to meandering core of event or pulsation in strength of event. The degree of simultaneity of an events' being sensed at several "outstations" may also provide insight into this problem.There is no easy solution to our apparent inability to determine the presence of systematic/coherent horizontal variations in flow (such as Langmuir Cells), although ABSS may prove useful in defining these variations.

III. Larger Scale (greater than 100 m vert., greater than 10 kms horiz.)

1. Long-Range HEBBLE Goals

a. HEBBLE I through 'n': The degree of completeness of the whole HEBBLE effort relates to the extent that the scales of interest are expanded. HEBBLE I will focus on bedform scales of one to 10's of cm (crag and tail, possibly with

or without longitudinal ripples?). The natural progression in scale would make HEBBLE II focus on the meters to 10's of meters bed forms, e.g. longitudinal furrows; and mudwaves with 100's of meters to kms scale might logically comprise the focus of HEBBLE III. The largest current-produced drift deposits of 10's to 100's of kms could be HEBBLE IV material. The relationship of all of the above, in whatever order, to regional marine geologic problems of ocean basin scales will probably continue to excite many P.I.'s involved (and some not involved) for some time to come.

b. Some additional considerations: It is important to understand "upstream" effects of the New England Seamount chain on our present HEBBLE area and consider its implications (and those of other physiographic features) on the Gulf Stream Gyre, the classical WBUC, and the deeper, more energetic southwesterly flow found in the HEBBLE area. It has been suggested (Hollister, personal communication, 1979) that the HEBBLE area is a transit region for material eroded/transported from well known northern sources (Labrador, Irminger, Norwegian Seas) to the sediment sinks south of Cape Hatteras (Blake, Caicos, Antilles Outer Ridges).

HEBBLE Advisory Committee Report

Introduction

The purpose of this report is to provide the HEBBLE Executive Committee with an evaluation of project plans as represented in the Nowell document and as presented by project participants during the March 1980 meeting in Keystone, Colorado. It is understood that this report also will be made available to the project sponsors and project members.

Our intent is to be relatively critical under the assumptions that a neutral document will be of little benefit to the project administrators, that project deficiencies are more easily corrected if pointed out at an early stage and that the project sponsors already know that the core of the project is sound and of high scientific merit. We are aware that some deficiencies arise due to the apparent unavailability of suitable principal investigators, yet we feel that the project administration is sufficiently innovative to find ways to fill these gaps and that they must be filled if the program is to remain healthy.

The HEBBLE Advisory Committee consists of the nine members. Only five of these individuals (Gordon, Grant, Krone, McCave, and Smith) were present at the Keystone meeting and participated in writing this report. Only two members of the Advisory Committee were familiar with project plans and project goals prior to the March 1980 meeting. Nevertheless, we feel that sufficient breadth of expertise is represented by the five man group to accomplish the intended objective and that sufficient information was made available to this group during the meeting.

The Advisory Committee strongly supports the HEBBLE plan and it recognizes that the project is filling a critical scientific need in the area of benthic boundary layer research. It also recognizes that the problems being addressed by HEBBLE are very difficult ones and that a truly integrated multidisciplinary approach is essential to their solution. Project participants are to be complimented on the degree of interdisciplinary cooperation displayed to date.

In general, the major facets of the problem are covered and a good balance has been struck between field observation and laboratory experimentation. The theoretical component of the program also is sound, but it needs to be expanded in several areas including the modeling of cohesive sediment transport and bed form dynamics and it needs to be more tightly tied with the field and laboratory aspects of the program.

During the past year the HEBBLE project has begun to display a more focused approach to benthic boundary layer investigations -- one in keeping with modern oceanographic research. Also the participants have begun to show a greater degree of sophistication in regard to interdisciplinary research. The diverse set of goals and interests represented by participants in the first Keystone meeting has been molded into a fundable program and with a small additional effort on the part of the Executive Committee a first rate scientific project can be expected to evolve. This trend is to be encouraged. Also the trend toward greater interdisciplinary understanding of bottom boundary layer problems is to be encouraged.

Comments on Some General Program Elements

A. Benthic biology program

Although primarily a service component, the HEBBLE biological investigations provide an opportunity for some new and interesting ecological research. This component of the project is well organized, well directed and essential from a sedimentological point of view. The degree of interdisciplinary effort on the part of the participating biologists certainly is to be commended.

The classification of organisms in terms of functional groups is an extremely useful approach. The studies carried out to date have been valuable for elucidating the effects of organisms on the roughness parameter and on critical shear velocities. However, we recommend greater emphasis be placed on examination of the role that organisms have in putting material directly into suspension, hence, maintaining a mobile layer in the immediate vicinity of the sea bed, despite the cohesive nature of the bed. Also the advisory committee recommends that the effects of organisms on remolded cohesive beds be examined at the earliest possible moment in the project.

B. Near bottom flow and sediment transport measurements

Although the program elements concerned with making near bed flow and flow related measurements have been well thought out, there are a few areas in which some additional effort may be necessary. As has been recognized by the project, boundary shear stress cannot be determined from velocity profiles alone in suspended load transporting flows. Therefore, precise sediment concentration profiles or shear stress measurements or both are required. The problem arises because suspended sediment induces flow stratification which causes a significant reduction in the magnitude of the momentum diffusion coefficient, hence an apparent change in von Karman's constant when a linearly varying eddy diffusion coefficient profile is assumed. If a logarithmic equation is fit to the velocity data and the apparent reduction of von Karman's constant is not accounted for, the resulting shear velocity calculated from the slope of the velocity profile absorbs the error. Of course, von Karman's constant does not in fact change, but rather the simple linear eddy coefficient profile, hence the logarithmic velocity equation no longer strictly applies. Nevertheless, under most sediment-transporting situations the shape of the velocity profile does not deviate much from a logarithmic curve and unless very accurate current meters are employed, the usual data analysis techniques do not permit identification of this problem.

In the HEBBLE deployments, mean flow and shear stress measurement will be made above the region of potentially greatest effect due to suspended sediment stratification. Therefore, it would be wise to have sediment concentration measuring devices in the lowest few tens of centimeters of the flow. If flow stratification effects do arise from the transported material, then sediment concentrations will be relatively high and devices such as those used in shallow water probably will be suitable. In any case care should be taken to employ sensors that do not disturb the flow at the measurement site. In particular, devices smaller than those presently suggeted for the HEBBLE lander should be used. The

measured velocity profile also ought to be extended through this region and a scanning two-axis laser velocimeter would seem the most desirable way to accomplish this task. Shear stress measurements in the immediate vicinity of the boundary are not likely to be of great value due to the considerable effect that the bottom topography has on stress profiles. Here it might be noted that near-bed velocity profiles are also affected by bottom topography; however, the effects on stress profiles are much greater and much more difficult to account for.

The microtopography problem is a serious one and needs to be considered in detail. The Advisory Committee recommends that numerous random samples of bed microtopography be obtained using a laser or an acoustic scanner or by stereo pair photography. This should be done with an accuracy sufficient to permit reproduction of all of the salient bed features in a laboratory flume. In this way, flows with shear velocities similar to those of interest at the HEBBLE site can be established over the reproduced beds, permitting the roughness parameter (Z_0) to be determined and its dependence on shear velocity and bed parameters to be evaluated. In addition, local values of velocity, shear stress and boundary shear stress can be measured over such a bed when reproduced in a flume. Skin friction experiments are not worthwhile under field conditions because sensor placement relative to a bed of known topography with the required precision is not presently possible without extreme cost and considerable flow disturbance.

It is not necessarily expected that precise, general expressions for the variation of Z_0 in terms of bed and flow parameters can be produced by such experiments but it is felt that the values of the roughness parameter to be expected due to microtopography alone can be constrained within a factor of five or less. Such a constraint will prevent the use of this parameter as an adjustable coefficient, thereby enhancing the usefulness and credibility of the near bed flow measurements considerably.

The Advisory Committee feels that an acoustic transducer to determine the thickness of the bed load layer, if there is any material moving in this mode, is essential. Devices like the one sold by Bob Lowe of the Scripps Institution of Oceanography are capable of determining both bed elevation and bed load transport layer thickness and we suggest that several such sensors be used during the various HEBBLE deployments. Bed load layer thickness is related to effective bed roughness in sediment transporting situations. Furthermore, if any bed load transport is occuring, and it is not unlikely that foram tests are transported in this mode at times, this component of sediment transport can be extremely important in regard to the generation of bed forms. The long range goal of HEBBLE appears to be to examine various types of bed forms so this component of sediment transport must not be neglected. In contrast there appears little that can be done with useful precision in regard to measuring bed load fluxes or in regard to measuring concentrations in the bed load layer.

It would be desirable to have 2 additional BASS sensors situated above the expected log layer but still in the lower part of the planetary boundary layer; that is, at least six sensors are recommended. Once a one-dimensional model has been shown to work for the lower part of the

Ekman layer, velocity and stress fields can be more accurately extrapolated to the bed if measurements are available over a greater depth range. Here the model provides the form of the velocity profile to be least squares fit to the data. This approach is now used in estuarine and coastal investigations and can be employed to good advantage during HEBBLE. Also it should be noted that the model used in conjunction with measured velocity, shear stress, and ambient density profiles is necessary to provide the vertical momemtum diffusion coefficient field and that the latter parameter is needed in the Ekman layer as well as in the log layer for the sediment transport calculations.

Determination of several fundamental physical parameters in the HEBBLE experiments depend on an accurate characterization of the lower part of the planetary boundary layer. For example, measurements of the mean current profiles in this zone determine roughness length and bottom stress. In view of the critical role these current measurements play in interpreting and modeling both sediment transport and the dynamics of the outer flow, it is recommended that the current sensors used be numerous, redundant and very accurately calibrated. They should be numerous enough (six sensors suggested) so that: 1) if the thickness of the boundary layer is reduced in slower flows, at least three or four sensors remain in the logarithmic region; 2) so that measurements can still be made in the event of a failure of one or two sensors; 3) so that adequate statistical information is provided on the goodness of fit to the logarithmic profile. The latter allows a more quantitative estimate of the precision of the derived values of Z_0 and U_*.

In terms of presently planned sensors, sufficient redundancy should be provided by six BASS sensors and six rotor current meters. This assumes that the rotors are accurately calibrated for flows with the anticipated levels of turbulence and that the BASS sensors have demonstrably stable zero calibration, adequate for long-term mean flow measurement.

C. Mesoscale physical oceanography

In order to understand the oceanographic framework into which the HEBBLE microscale experiment is to be imbedded and in order to provide some knowledge of the fluid mechanical forcing that occurs in the neighborhood of the HEBBLE site, a mesoscale physical oceanographic component of the project is essential. However, owing to the cost of such a program, the number of instrument sites and the number of sensors to be displayed at each site must be held to a minimum.

The present plan to have four outstations surrounding a more heavily instrumented central mooring is acceptable but minimal. Neither the number of stations nor the number of instruments to be set at each station should be reduced further. In contrast, it is not clear that a significant gain would accrue from adding one or two more outstations. In any case, this moored current measurement program must be supplemented by a lengthy and detailed hydrographic survey of the general HEBBLE area. From this ship-supported investigation of the temporal and spatial variability of temperature, salinity, density, and sediment concentration fields will have to come the bulk of the physical oceanographic

understanding of the fluid mechanical setting. The survey ship will have to be on station long enough to catch an event and considerable effort will need to be placed on assessing the temporal variability in properties at fixed sites as well as on determination of regional structure. Such an investigation will be of considerable assistance in elucidating and understanding the transport of suspended particulate matter as well.

Many of the planned HEBBLE measurements will be recorded as a sequence in time. It is important that the instrumentation and experimental design provide adequate data for interpretation of these series records in a way that unambiguously distinguishes between temporal and spatial effects. For example, in order to interpret a local increase in suspended particulate material (SPM) as an upstream "erosional event", there must be sufficiently accurate measurements of current directional variation and horizontal SPM distribution to eliminate the possibility that the observation is merely a lateral meander of a more or less steady-state core of high-velocity, high-SPM WBUC. <u>It is suggested that the experimental plan include a combination of current directional information with periodic nephelometer transects of the WBUC to monitor the transverse distribution of SPM.</u>

D. <u>Flow and sediment transport modeling</u>

An extremely important part of the HEBBLE program is the modeling component. As the situation now stands an excellent foundation for first rate work in this area has been developed. However, the Advisory Committee sees this facet of the program as being understaffed and somewhat less active than should be the case. In particular <u>we feel that a cohesive sediment transport model for the HEBBLE area should presently be under development, that preliminary work on the bed form problem should be underway, and that Weatherly's present model should be run for various parameter ranges of interest at the HEBBLE site.</u> In addition, more thought should be going into integration of the models with the field and laboratory data and into specifying what variables are required for the models as well as how these are to be procurred to the required accuracy. Finally <u>more effort should be going into the assessment of potentially useful multidimensional physical oceanographic models.</u> Clearly this is more work than can be accomplished by one small modeling program and Weatherly's efforts need to be supplemented, especially in the cohesive sediment transport area.

E. <u>Bed property measurements</u>

Physical properties of the bed are important to the objectives of the HEBBLE project in three ways. The stratigraphic characteristics of sediment profiles are a basic source of information on the geologic history of benthic deposits. Knowledge of the mechanical properties of the bed profile will facilitate the design of instrument support structures that will be reasonably stable under the stresses imposed by currents. Finally, erosion of bed material and deposition of suspended material are central processes in the development of nepheloid layers and the formation of bed forms, and quantitiative descriptions of the

properties of the bed that determine the rates of erosion or deposition are vital to the success of the project. These remarks concern mechanical properties of the bed relevant to structure support and sediment transport.

Cohesive sediment beds under sustained loads typically deform over long periods, and such beds are very weak, compared to terrestrial soils. One of the experiments described at the Keystone meeting indicated that settling of a current meter string significantly affected the measurements. The performances of the Central Lander and the BOM will be seriously affected if differential settlement or overturning occurs. The development of stable support systems will require the information obtained by the proposed geotechnical measurements on sediment cores. This program should include measurements of properties of the bed to depths that are sufficient for the design and the analytical and physical evaluation of both pile- and footpad-mounted instrument support systems before their deployment. Instrumentation should be placed on each support system to monitor changes in its elevation and inclination during deployment.

Rates of erosion and deposition depend on the properties of the bed surface that is exposed to currents. The depth of bed erosion during the prevalence of the currents described at this meeting will be very small: probably no more than a few centimeters. Further, erosion and deposition rates are determined by hydraulic forces on individual exposed grains or thin layers of flocculent material. Evaluation of deposition and erosion rates require hydraulic measurements on the uppor portion of the bed.

Research on hydraulic erosion of soils has shown that mechanical measurements of shear strength do not correlate reliably with critical shear strength for surface erosion. Mechanical measurements such as cylindrical or wire mesh penetrometers and the vane shear apparatus do show changes in soil structure with depth and can be utilized to indicate depths of such changes below the bed surface. The deformation and mode of failure of soil during the vane shear test is complex and interparticle forces are totally unlike the bond rupture that occurs during erosion. The cylindrical penetrometer has more nearly simple shear at failure and can easily be made sufficiently sensitive to be useful in surface material. Neither instrument has been shown to be a substitute for hydraulic measurements, however.

The proposed Sea Flume II will measure erosion rates and critical stresses for deposition and erosion in-situ. In view of the central importance of these data to the modeling and attainment of project objectives, the design, construction, and testing of Sea Flume II should begin as soon as possible. Design should include instrumentation to assure placement at a suitable site with an adequate seal to the bed. Sampling of the bed adjacent to the flume should also be facilitated. Deployment should be preceded by testing in the laboratory and in shallow water.

In order to design the Sea Flume II program for maximum effectiveness, to provide preliminary information to the model, and as a hedge against delay or failure of the Sea Flume II deployment, laboratory flume experiments on reconstituted beds should begin immediately. These

experiments should utilize sea water at sea bed temperature and material from sediment box-cores and be conducted in a suitable flume. The cores should be taken from the selected area and preserved wet until used. Beds formed by sediment suspensions maintained at concentrations less than 100 mg/l and deposited at low current velocities should subsequently be eroded at various rates to determine resistance to erosion at various depths below the bed surface. Shallow water organisms could be included in a second series of tests to estimate the contribution of oganisms. These experiments require long running times.

F. Sedimentological investigations

1. Optical sensors - calibration problems

The calibration of the optical sensors has the problem that the same volume of water sampled for mass concentration is not scanned by an optical sensor. In the case of the transmissiometer run on a wire with a CTD and rosette of Niskin bottles, adjacent water volumes can be scanned and sampled. The same is in principle true of the LDGO nephelometer. It is essential that the most comprehensive calibration in gravimetric terms be undertaken. This will probably be best undertaken on the wire when a large number of points can be obtained from a few hydro-casts. A particular problem is the ambiguity likely to be found in the region near the bed where appreciable quantities of sand (up to 20%) may at times be in suspension. The sensitivity of the transmissometer to mass concentration is greater for fine SPM than for sand, thus higher concentrations of sand may yield the same values of transmission as lower concentrations of fine SPM. If useful information is to be obtained optically in the 0 to 5m layer a separate calibration should be made for this region involving accurately located samples close to the bed. The size distribution of the samples as well as their mass concentration should be determined.

2. Sediment settling velocity

The settling velocity (mass) frequency distribution is a key parameter entering into the models of suspended sediment behavior in turbulent flows. It should change in relation to flow conditions and ideally should be determined at several heights in known flow conditions (it may well not change by increase in w_s with increase in $u*$ as one might anticipate). The concentration-weighted settling velocity ($\Sigma C_{i} w_{si}/\bar{C}$) will be of more importance in models. The three efforts in the project to obtain this distribution (Zaneveld, optical settling tube; Southard, gravimetric settling tube; and Carder, holographic particle velocimeter) are complementary. The optical method may suffer from the ambiguity referred to in the preceeding item, and the holographic method which counts particles will have difficulty in providing a mass settling velocity distribution. On the other hand, it will give useful information on settling velocity of different particle types. Again, this parameter is likely to be most important in the few meters closest to the bed where sediment stratification is most likely. Some effort should be devoted to determining w_s in this region.

3. Sediment fluxes

Fluxes at a point may be obtained by integration of the

$(C_z U_z)$ profile. This can be compared with model predictions. On a scale of several kilometers the concentration field is expected to be variable (cloudy), and as the array of outstations is unlikely to sample that cloudiness properly, it is most unlikely that the flux field will be determined. Only in the event that this concentration is uniform over the 10 km scale (a "fog bank"), will the flux field and net fluxes be meaningful. This means that estimation of distributed erosion and deposition by input/output calibration for a box (involving differences of these quantities with large error) will probably be impossible.

4. Sediment traps

Although useful qualitative information may be obtained concerning the vertical distribution of large-particle properties allowing assessment of material provenance, the derived horizontal and especially vertical fluxes have such a high uncertainty as to make the exercise of doubtful value. This is because the behavior of flow of different speeds and turbulence levels carrying particles of differing settling velocities is not known in relation to trap form and degree of tilt in the flow. At best traps are large-particle collectors with an unknown degree of bias.

5. Macro-Topography

Accurate knowledge of the bottom topography at the HEBBLE site is essential to the interpretation and generalization of both vertical Reynolds stress profiles obtained from BASS and velocity profile measured using BASS and conventional rotor methods. Topographic information is needed to separate contributions to the total drag on the flow made from (1) distinct roughness scales present at the sea bed and (2) sediment transporting influences associated with bed load transport. These represent important input parameters to the modeling effort as well. Furthermore, the size and the location of topographic features relative to current sensor locations must be known to resolve horizontal and vertical variability in velocity profiles associated with the gradual adjustment of the flow to the change in roughness scale.

Topographic features at the HEBBLE site on the vertical scale of one meter (or less) over longitudinal scales of 100 meters or less are of particular importance. Resolution of intermediate scales down to the scales of the microtopography should be included. The use of a system such as Deep Tow to measure the site topography is probably adequate to resolve the larger scales provided careful attention is given to (1) the number of survey tracks necessary to characterize the site adequately, the upstream and downstream extent of the surveys, and the question of vertical resolution of Deep Tow, or a similar system. Local topography in the vicinity of the current sensors should be monitored during deployment. Possibly cameras or acoustic devices may be used for this purpose. In addition careful consideration should be given to deployment of more than one BASS to allow assessment of the turbulent response to flow over distributed microtopography.

H. HEBBLE Lander

The present configuration of the HEBBLE Lander may create significant disturbances to the flow field past it. To minimize the effect of the frame members, mounts and individual instruments upon measurements made

from the Lander, JPL has proposed to orient the Lander in a preferred direction during deployment. Regardless of the success of the positioning plan, flow disturbance problems may still occur. For a given current direction the bed downstream of the Lander can be modified by sediment erosion or deposition associated with the disturbed flow around the Lander. Since the current may not always come from the preferred direction, it is conceivable that the bed all around the Lander will be disturbed. Thus, even during periods of current from the preferred direction, the Lander may affect the observed sediment flux and the flow field. Other problems with the Lander which may adversely influence measurements include scour around the feet of the Lander, uneven settling, and depressions caused by impact of deployment.

Documentation of flow disturbances associated with the Lander should be made. This should include the interference between individual instruments and structural members of the Lander as well as the bulk effect of the Lander on the flow field and bottom around it. An alternative positioning scheme should be considered; possibly the use of a small motor driven propellor and compass system rather than the present vane configuration. Other structural forms for the Lander should be investigated, e.g., a vertical pile. If the present system proves to be the best choice, careful consideration should be given to removing some instrumentation, such as one BASS array and transmissometer, and placing them separately at a nearby site.

General Comments

A. Project Management

The upcoming field experiments, instrumentation development, associated data processing and analysis and interaction among P.I.'s will put heavy demands on the time of scientists involved in HEBBLE. At the same time the demand for logistics, cruise plans and meetings among JPL, and HEBBLE scientists will also increase. It would be a good idea to consider hiring a program coordinator who has the technical background to make scientific and engineering decisions on a daily basis, needed to keep the program running smoothly, but who is responsible to the HEBBLE Executive Committee. The intent is to enable scientists to concentrate on major scientific issues and questions and still keep the technical management of the program running smoothly. A suitable level of experience would be several years work in the field post bachelor's, a new PH.D. or experienced M.S.

HEBBLE has reached a level where its scientific goals should be well focused. It is important to put top priority on the achievement of these scientific goals. This means that the essential tasks to achieve the goals must be identified, important scientific questions must be stated as testable hypotheses, provisions must be made to carry out the tasks, and responsibilities assigned. Individual investigators must make the assigned task their primary goal and streamline their projets to carry them out. Other questions of interest to individual scientists, but not essential to the goals of HEBBLE should be addressed only after the primary tasks of HEBBBLE are completed.

B. Information Exchange

As the accumulated volume of HEBBLE-related data grows and individual investigators become more dependent on the results of colleagues for progress in their own studies, some more formal arrangement should be initiated for keeping HEBBLE participants mutually informed of each others most recent output. A suggested first step in this direction is a quarterly, informal newsletter, in which principal investigators are obliged to report the current status of their data treatment along with information on the format and availability of results already obtained. Principal investigators should give high priority to design of software and procedures to facilitate early data reduction into a form understandable to the broad range of disciplines represented by the HEBBLE community.

The funding agencies are urged to provide adequate resources for such prompt data reduction and early distribution of results throughout the HEBBLE organization.

C. Program Scientific Objectives versus P.I. Measurement Tasks

The program has been structured into a series of defined scientific problems related to inner layer, benthic boundary layer, and larger scale aspects. These scientific problems are not addressed with one to one correspondence by individual P.I. measurement programs. We think that the Executive Committee must play a strong coordinating role to ensure that the outcome of the Experiment is a real attack on the scientific problems rather than simply the P.I. program output. The committee must also identify (with assistance from the Advisory Group!) areas in which expertise is lacking and recommend its incorporation to program management. In a program where individual P.I.'s do not have to have their proposals approved by the Executive Committee there is always the possibility of some tasks not being done. Clearly, frequent and close cooperation between program management and the committee will ensure that all the necessary tasks are taken onboard (and that unnecessary ones are cast adrift!).

Acknowledgements

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APPENDICES

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Terry Ewart	-- APL/UW
Cliff Gordon*	-- Naval Research Lab
Bill Grant*	-- WHOI
Nelson Hogg	-- WHOI
Ray Krone*	-- UCal/Davis
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* present at Keystone III conference

HEBBLE Executive Committee

Charley Hollister (Chairman)	-- WHOI
Pierre Biscaye	-- L-DGO
Peter Lonsdale	-- SIO
Peter Jumars	-- UW
Arthur Nowell	-- UW
Georges Weatherly	-- Florida State
Sandy Williams	-- WHOI
Mark Wimbush	-- URI

SCHEDULE

Tuesday, March 11, 1980

-- morning

Opening remarks by Hollister, Craig
History and legacy of Keystone I and II
Objectives for first long-term HEBBLE
Long-range objectives (HEBBLE II on)
Funding prospects -- Milder, Goodman, Pyle

-- afternoon

Advisory Group meets with Executive Committee
Deep Tow feasibility meeting

Wednesday, March 12, 1980

-- morning

Data presentations from KNORR and CONRAD 1979 cruises:
- Biscaye (suspended particulate matter and radon measurements)
- Zaneveld (optical transmissometry)
- Wimbush (current meter results)
- Weatherly (rotor and thermistor data from the Chandelier)
- Richardson (silicates)
- Silva (sediment shear strength)
- Tucholke (surface sediment texture)

-- afternoon

Informal Working Group meetings

-- evening

Inner Layer Working Groups meet:
- Bed response to stress
- Fluid dynamic parameterization
- Near-bed fluxes of suspended particulate matter

Thursday, March 13, 1980

-- morning

Inner Layer Working Group reports: Jumars, Irish and Gardner
Benthic Boundary Layer Working Groups meet:
- One and two-dimensional modeling
- SPM flux and dynamics
- Vertical and horizontal coherence of SPM, flow and their interaction

-- afternoon

Informal JPL/Project Director meeting
Physical Oceanography meeting

-- evening

April KNORR cruise participants meeting

Friday, March 14, 1980

-- morning

Benthic Boundary Layer Group reports: Williams, Mayer and Richardson

Larger Scale Plenary Session:
- Temporal and spatial variability of circulation and SPM
- Relationship to WBUC and Gulf Stream system
- Distribution of bedform types and sedimentation of Scotian Rise

JPL Revised program plan presentation, schedule discussion and system design

Discussion of future HEBBLE sites and methods of study

-- afternoon

Executive Committee meeting with Advisory Group

-- evening

Advisory Group meeting

<u>Saturday, March 15, 1980</u>

-- morning

Advisory Group meets with Executive Committee to present recommendations and critique

Larger Scale summary: Tucholke and Pfirman

Meeting summary: Nowell and Jumars

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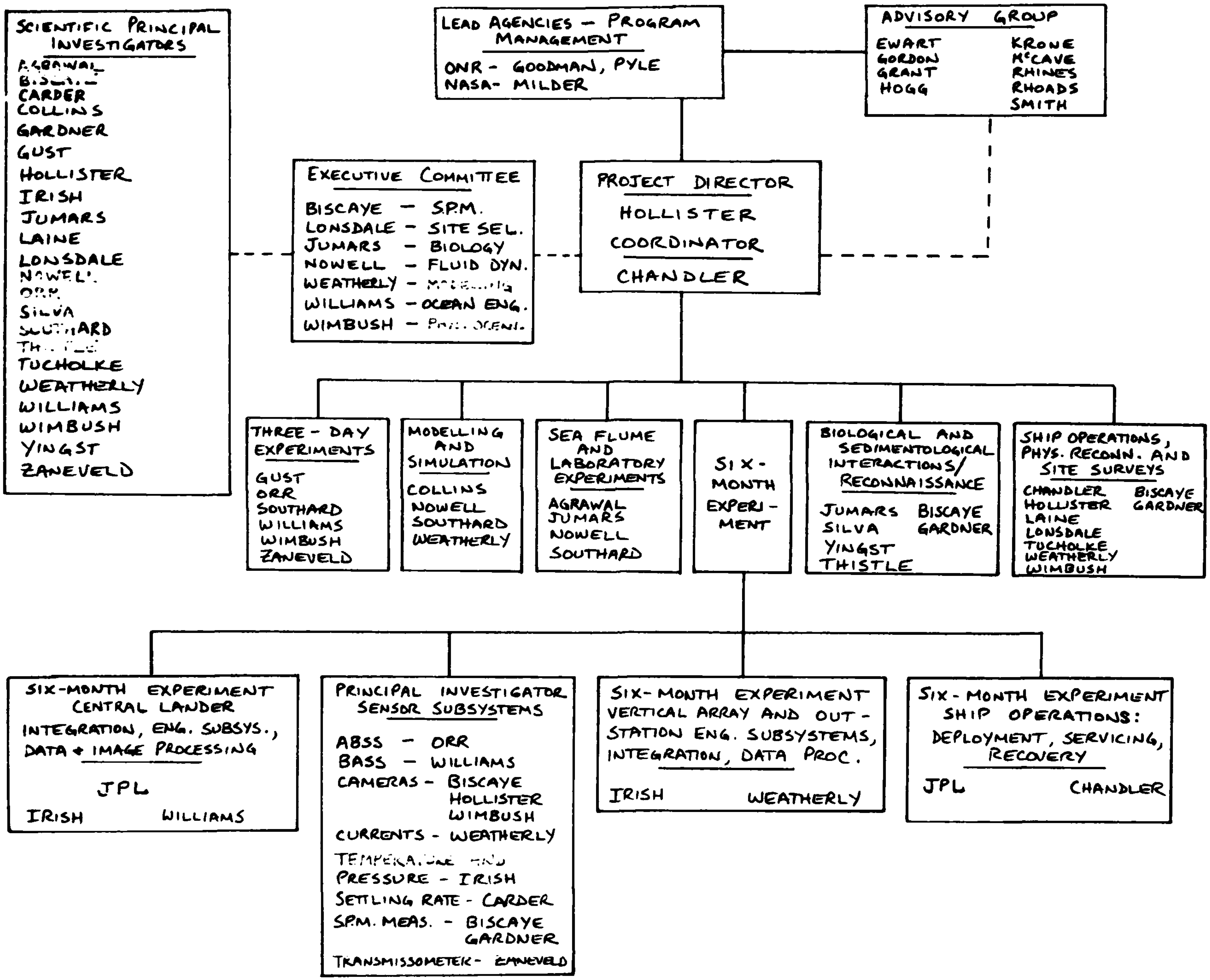
HEBBLE: Instrumentation

System	Principal Investigator(s)	System Components
Acoustic Backscatter	Orr	Acoustic Backscatter
Benthic Acoustic Stress Sensor (BASS)	Williams	Acoustic current meter, height gauge, thermistors, rotors
Beam Transmissometer	Zaneveld	Optical Transmissometer
Biological Sampling	Jumars Thistle Yingst	Box core, Gravity core
Bottom Ocean Monitor (BOM)	Biscaye Gardner	Camera, Current Meter, Nephelometer
Central Lander	Collins Irish Williams	To be determined
Chandelier	Weatherly	Rotors, Vanes, Thermistors
CTDN	Weatherly Zaneveld	CTD, Rosette Sampler, Transmissometer
Current Meter Array	Irish Weatherly Wimbush	Modified Geodyne 101 VACM's, Thermistors
Deep Tow	Lonsdale	120 KH_z side scan sonar, 4-6 KH_z Sub-Bottom profiling, transponders, cameras

Electrical Size Sensing	Richardson McCave	Coulter Counter
Geotechnical Properties	Silva McCave	Vane shear, water content
Light Scattering	Biscaye	Lamont nephelometer
Outstations	Irish Weatherly	Current Meters, thermistors transmissometers, others TBD
Photographic Systems (cable-lowered)	Biscaye Gardner Hollister Tucholke	Camera/strobe
Photographic Systems (frame-mounted)	Biscaye Gardner Hollister	Close-up camera/strobe 35 mm stereo cameras
Sea Duct	Nowell Collins	Inverted recirculating duct with LDV
Seaflume	Southard McCave	Inverted flow-through flume
Sedimentological Properties	Biscaye Gardner Shor Tucholke	Box, Gravity Core samples, SEM micro- fabric
Settling Velocity Sensors	Carder Zaneveld Southard	Optical holographic imager, settling tube, camera, transmissometer, bottom settling tube with timed partition intrusion
Triffid	Wimbush	VACM's, camera, transmissometer
Turbulence Sensors	Agrawal Gust Williams	LDV, hot wire, acoustic current meter
Vertical Array	Weatherly Irish	same as outstations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NASA - MILDER
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COLLINS
NOWELL
SOUTHARD
WEATHERLY
SEA FLUME AND LABORATORY EXPERIMENTS
AGRAWAL
JUMARS
NOWELL
SOUTHARD
SIX - MONTH EXPERI - MENT
BIOLOGICAL AND SEDIMENTOLOGICAL INTERACTIONS/ RECONNAISSANCE
JUMARS
SILVA
YINGST
THISTLE
BISCAYE
GARDNER
SHIP OPERATIONS, PHYS. RECONN. AND SITE SURVEYS
CHANDLER
HOLLISTER
LAINE
LONSDALE
TUCHOLKE
WEATHERLY
WIMBUSH
BISCAYE
GARDNER
SIX-MONTH EXPERIMENT CENTRAL LANDER
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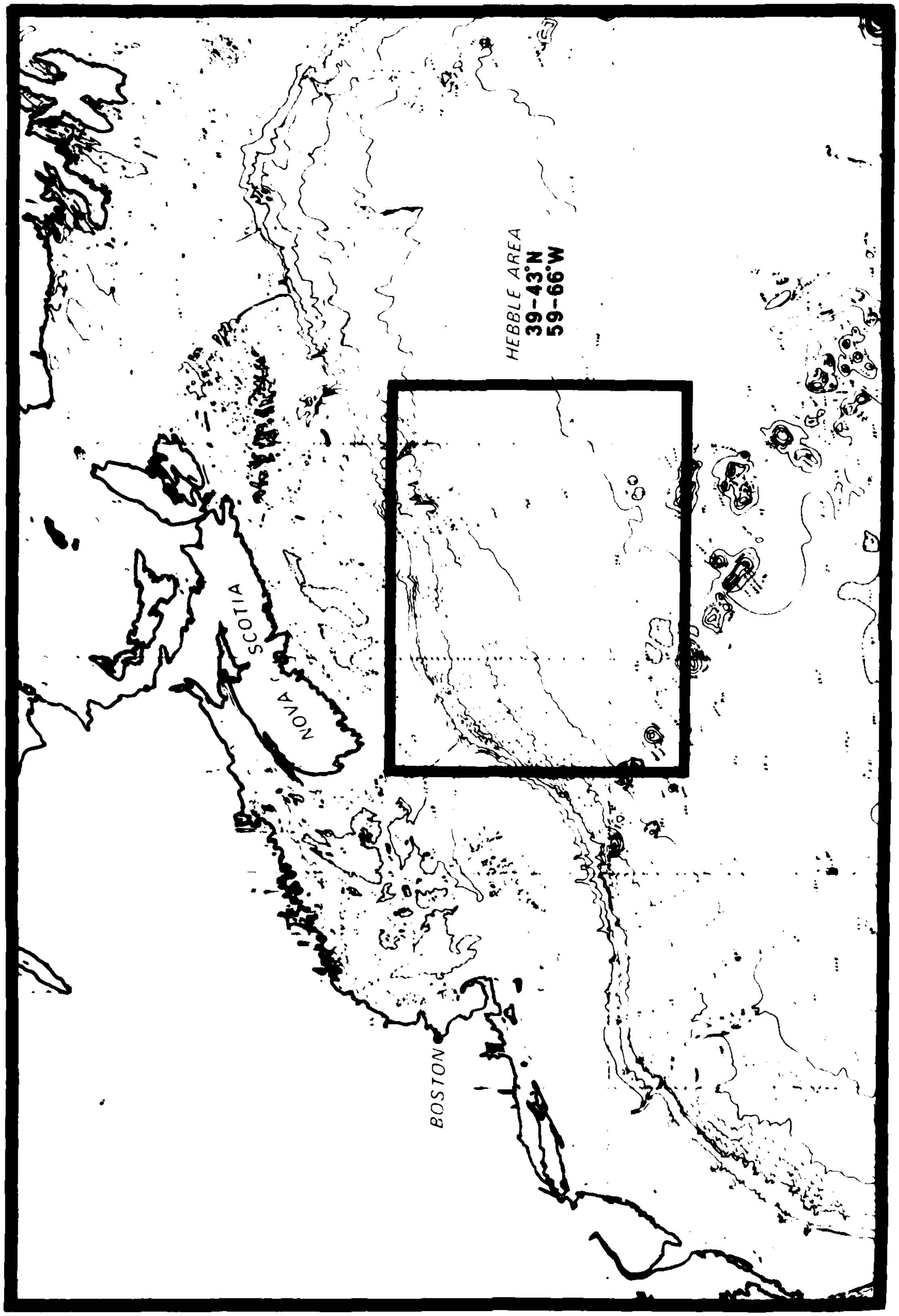
IRISH
WILLIAMS
PRINCIPAL INVESTIGATOR SENSOR SUBSYSTEMS
ABSS - ORR
BASS - WILLIAMS
CAMERAS - BISCAYE
HOLLISTER
WIMBUSH
CURRENTS - WEATHERLY
PRESSURE - IRISH
SETTLING RATE - CARDER
S.P.M. MEAS. - BISCAYE
GARDNER
TRANSMISSOMETER - ZANEVELD
SIX-MONTH EXPERIMENT VERTICAL ARRAY AND OUT-STATION ENG. SUBSYSTEMS, INTEGRATION, DATA PROC.
IRISH
WEATHERLY
SIX-MONTH EXPERIMENT SHIP OPERATIONS:
DEPLOYMENT, SERVICING, RECOVERY
JPL
CHANDLER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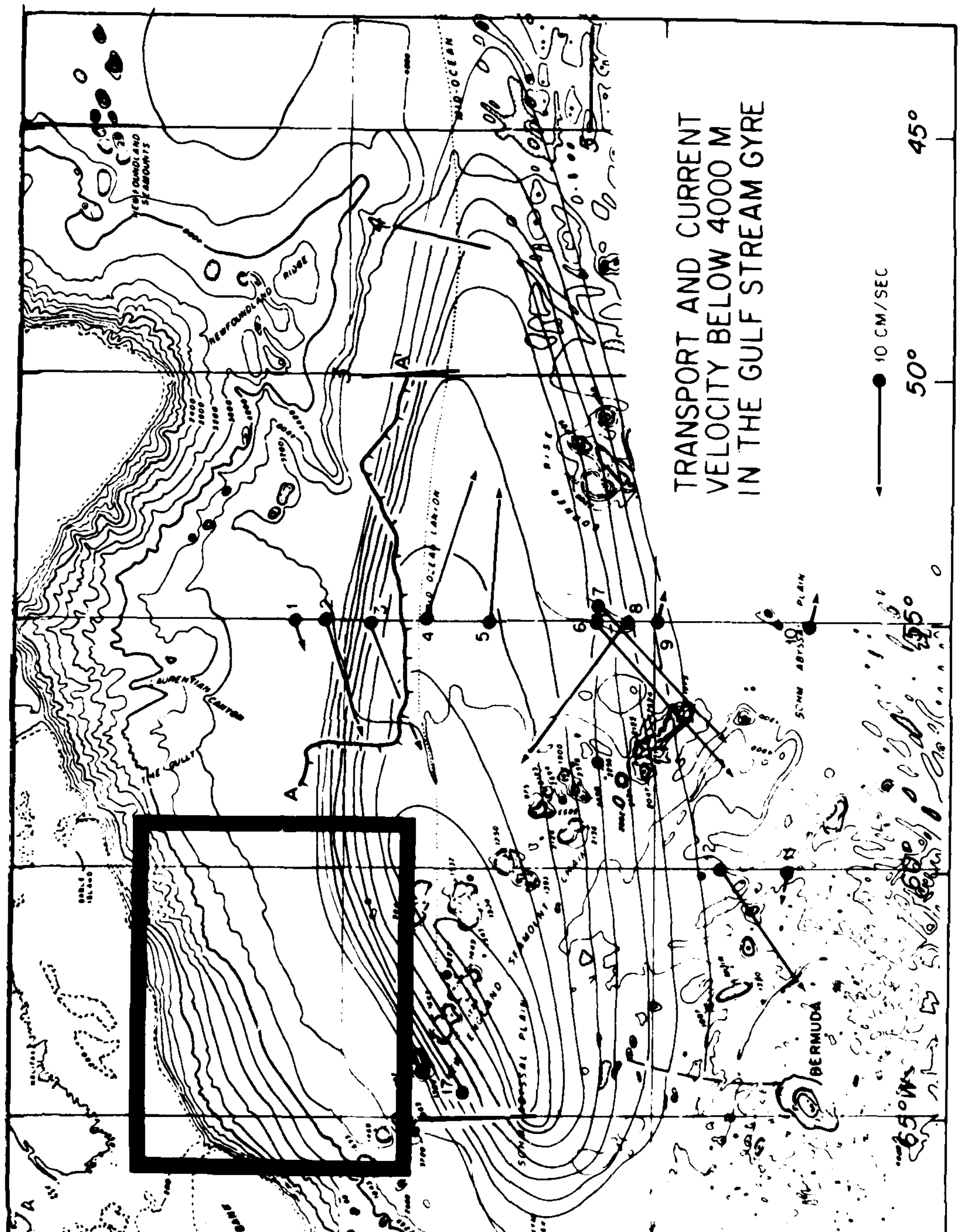
59-66°W
NOVA SCOTIA
BOSTON


TRANSPORT AND CURRENT
VELOCITY BELOW 4000 M
IN THE GULF STREAM GYRE
10 CM/SEC
50°
45°
55°
60°
65°W
40°N
35°
NEWFOUNDLAND RIDGE
NEWFOUNDLAND SEAMOUNTS
LAURENTIAN CANYON
GEORGES BANK
BERMUDA
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THE THIRD ANNUAL REPORT OF THE HIGH ENERGY BENTHIC BOUNDARY LAYER EXPERIMENT by Charles D. Hollister, Arthur R.M. Nowell and J. Dungan Smith. 48 pages. July 1980. Prepared for the Office of Naval Research under Contract N00014-79-C-0071; NR 083-004.

A meeting was held March 11-15, 1980, to develop and refine the hierarchy of problems to be addressed by the high energy benthic boundary layer experiment. This document outlines revised program goals and the critical scientific tasks needed to attain those goals. Also included is an interim "state of the program" report and a critical review by the Advisory Committee.

1. Benthic boundary layer
2. Bedforms
3. Current measurement

I. Hollister, Charles D.
II. Nowell, Arthur R.M.
III. Smith, J. Dungan
IV. N00014-79-C-0071; NR 083-004

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